Comparison of Freeway Simulation with INTEGRATION, KRONOS, and KWaves

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ABSTRACT

The ability of three software models to simulate freeway operations was tested under moderate-to-heavy traffic with and without an incident, and heavy traffic. Sensitivity with respect to freeway mainline lanes, capacity and jam density also was inspected. Cross-sectional (spot) speeds obtained with AUTOSCOPE as well as segment average speeds obtained with instrumented vehicles were used for making objective comparisons. Overall, INTEGRATION and KRONOS gave better results than KWaves. INTEGRATION produced acceptable results for all traffic conditions but its lane-changing replication was not realistic, especially for on- and off-ramps connected with an auxiliary lane. KRONOS required the fewest modifications to achieve good results but it overestimated the benefits of adding a lane to the mainline freeway. KWaves98 is limited to the simulation of freeway operations under heavy traffic conditions. Its triangular modeling of the speed-flow relationship produces a delayed onset of and early relief from congestion. Outputs from these models can also provide estimates of LOS per the HCM.

1. INTRODUCTION AND BASIC THEORY OF TESTED SOFTWARE

Computationally complex computer simulation models for the analysis of traffic operations on freeways appeared in the late 1960s and the 1970s (e.g., FREQ, CORQ, INTRAS) and flourished in the 1980s (e.g., FRESIM, KRONOS, INTEGRATION). At the present time, sophisticated versions of several software combined with fast digital processing and low computing costs enable the realistic approximation of freeway conditions with simulation. This, in turn, eliminates the need for costly, time-consuming, risky, and often infeasible field experiments and provides a scientific basis for the evaluation of freeway management alternatives.

Three inexpensive simulation models, INTEGRATION (version 2.0*i* of 1996), KRONOS (version 8 of 1997), and KWaves98 (version 2.08 of 1999) were compared. All three software models are macroscopic to a varied degree: KWaves98 is purely macroscopic. KRONOS is macroscopic but it models merging, diverging and lane changing maneuvers. INTEGRATION is a mesoscopic model because although individual vehicles are traced through the network, lane-changing and car-following behavior are not modeled microscopically. Instead, the aggregate speed-volume interaction of traffic (u-q relationship) is used on each link. Among the tested versions of the software, INTEGRATION and KRONOS run under MS-DOS whereas KWaves98 runs under MS-Windows.

INTEGRATION was developed in the late 1980s by Van Aerde with the goal to simulate integrated networks; it was based in part on Yagar's CORQ corridor simulation and assignment model developed in the early 1970s. INTEGRATION determines vehicle speeds and lane changing using the subpopulation's headway which is calculated every $^1/_{10}$ of a second. The speed-headway relationship is derived from a macroscopic speed-flow relationship which is calibrated by the free-flow speed, speed at capacity, capacity and jam density (Van Aerde, 1995).

KRONOS was developed in the early 1980s at the University of Minnesota and has been under continuous refinement (Michalopoulos and Kwon 1991.) Version 8 uses a simple continuum model based on the L-W-R theory (Lighthill, Whitham, Richards). A finite differencing scheme with discretizing over space ($\Delta x = 100$ ft.) and time ($\Delta t = 1$ sec.) enables it to solve 1-dimensional, time-dependent, compressible flow containing shockwaves. KRONOS also accounts for accelerating, decelerating, lane changing, merging, diverging and weaving since these complex traffic phenomena only occur at specific freeway locations. In KRONOS, the flow-density relationship can be linear in light-to-moderate traffic conditions, that is, $u = u_f$ for all $k < k_a$ (k_a is a user input).

Leonard developed KWaves98, based on Newell's theory (Newell, 1993), with the objective to evaluate freeways under saturated conditions. Suspecting the validity of the relation between flow rate and density assumed by the simple continuum model (L-W-R theory), Newell presented a simplified theory of kinematic waves in highway traffic. The conservation of the volume of traffic is met by introducing a cumulative flow rate. The major parameters, such as flow rate, density, speed, delay, are derived from the cumulative demand and the actual cumulative flow. The triangular q-k relationship proposed by Newell avoids mathematical complexity. Newell theorizes that a shockwave occurs at the point where the slope of the cumulative flow versus time for any fixed location or the slope of the cumulative flow versus location for any fixed time is not continuous. KWaves98 models a single freeway mainline and it does not consider ramps.

The features of the tested software are presented first in terms of inputs, outputs and other significant attributes. Then, simulation results from two hypothetical cases and one real case are described. The ability of the three models to predict speeds was examined in the real case which included field estimates of speed.

2.   ATTRIBUTES OF TESTED SOFTWARE

Input, output, and optional features of the tested software are summarized in Table 1. INTEGRATION and KWaves98 inputs are entered into text files. KRONOS inputs are entered interactively through built-in input menus, which consist of layered questions and options. INTEGRATION and KWaves98 have a rather typical network description with links and nodes. KRONOS utilizes a window listing all common types of freeway segments which the user selects to add in the proper sequence. Free-flow speed (u_f) and jam density (k_j) are common inputs for all three software. INTEGRATION and KWaves98 require origin-destination (O-D) flows to estimate volumes at entry and exit segments. KRONOS requires hourly-equivalent volumes at all entry and exit segments.

INTEGRATION and KRONOS have explicit ramp metering settings as well as means to input capacity limitations on entry and exit ramps. INTEGRATION also can model signals at the entry of on-ramps and at the terminus of off-ramps. This offers a more realistic replication of platooning (on on-ramps) and queuing (on off-ramps). All three software have means to replicate incidents.

Basic outputs such as total travel, total travel time and average speed for the simulated freeway network can be read or derived from the output reports of all three software. Contours of flow, density, speed over time and/or distance (2- or 3-dimensional plots) are available in both KRONOS and KWaves98. Density output can be used in conjunction with the *Highway Capacity Manual* (HCM) for defining the level of service (LOS) on specific freeway segments.

INTEGRATION offers a fairly detailed visualization of the network while it is simulated. Through post-processing, KRONOS offers a time-scan, color-coded representation of density along the simulated freeway called *flow emulation*. Both animation and emulation are effective means of diagnosis and interpretation (e.g., bottleneck identification and shock wave propagation). INTEGRATION and KRONOS also produce consumption and pollution estimates. KWaves98 does not provide animation, flow emulation and environmental estimates.

In case of input errors, KRONOS objects in each input screen if entries are outside allowed limits. INTEGRATION reads input files in a predetermined sequence and when it finds an error, it produces an error file and ceases processing. This becomes tedious particularly when large or complex networks are modeled. KWaves98 operates in a similar fashion; its run-status window, however, offers a direct and quick notification of errors and warnings.

KWaves98 is a memory intensive application. Case 1 shown below is a small application. It runs quickly within 640 KB of memory with INTEGRATION and KRONOS, but it requires 17,000 KB with KWaves98. As a result, "crashes" were experienced in the simulation of larger networks with KWaves98, particularly when short time intervals were used.

3.   CASE STUDIES

Three case studies were investigated: (a) a simple freeway network with moderate-to-heavy traffic; (b) a simple freeway network with moderate-to-heavy traffic and an incident; and (c) a real case on H-1 freeway with heavy traffic. Case (a) was used for three basic sensitivity tests:
(i) effects of increasing the freeway cross section from 3 to 4 lanes;
(ii) effects of increasing the freeway capacity by 10%; and,
(iii) effects of increasing the freeway jam density by 10%.
The latter enable the models to increase density of vehicles which not only assists in replicating observed congested flows but also provides a better representation of Honolulu freeway traffic which is comprised mostly of compact cars and contains less than 1% heavy vehicles. The initial parameter settings for the three models are shown next.

Parameter	INTEGRAT.	KRONOS	KWaves
Mainline capacity (veh/hr/ln)	2200	2200	2200
Ramp capacity (veh/hr/ln)	1500	1500	N.A.
Delay speed (mph)	U_f	50	U_f
Free-flow speed, U_f (mph)	65	N.A.	65
Jam density, k_j (veh/mile/ln)	186	186	186
Density at Q_{max}	N.A.	58	N.A.
Speed at Q_{max}	40	N.A.	N.A.

In order to be able to provide closely comparable results, several manipulations of the original output were required. The two limitations were:

(i) Unlike KRONOS and KWaves98, INTEGRATION does not include a total delay estimate in its output, so delay was approximated as follows:

$$\text{Total Delay}_{INT2} = TTT(c_N) - TTT(c_{3N}) - [TT(c_N) - TT(c_{3N})] / AS(c_{3N}) \quad (1)$$

where:
$TTT(c_N)$ = total travel time at normal capacity (veh-hrs)
$TTT(c_{3N})$ = total travel time at 3 times normal capacity (veh-hrs)
$TT(c_N)$ = total travel at normal capacity (vehicle-miles)
$TT(c_{3N})$ = total travel at 3 times normal capacity (vehicle-miles)
$AS(c_{3N})$ = average speed at 3 times normal capacity

In other words, the travel time at three times the original capacity, $TTT(c_{3N})$, was employed in order to get estimates which are representative of *free-flow conditions,* and the travel time at normal capacity, $TTT(c_N)$, represents *prevailing conditions*. Their difference, adjusted for the possible deferred departures under congested conditions [the last term in Eq. (1)], is the delay. This necessitated the execution of INTEGRATION twice for each case examined. Note that $_{5N}$ was also tested; it produced identical results.

(ii) Since KWaves98 does not account for ramps, the total travel, total time and total delay on all ramps were excluded from those produced by INTEGRATION and KRONOS. For the same reason, the average speeds produced by INTEGRATION and KRONOS were calculated by averaging mainline statistics only, rather than using the overall average speed in the summary output.

3.1.   Simple Freeway Network with Moderate-to-Heavy Traffic

The network is depicted in Exhibit 1-(a) with a KRONOS graphic. The demand of the first on-ramp is light (250 veh/hr/ln) and unchanged through the 120 minutes of simulation. The demand on the mainline and the second on-ramp increased from moderate to heavy (mainline = 1,800 to 2,000 veh/hr/ln; second ramp = 700 to 1,050 veh/hr/ln) during the first 60 minutes and decreased slightly in the following 60 minutes. The proportion of traffic destined to the single off-ramp in the network is 73% from the mainline, 12% from

the first on-ramp, and 15% from the second on-ramp. Analyses similar to those in Wang and Prevedouros (1998) were done for the use of a lane striping file in INTEGRATION and concluded that only the off-ramp (link 9) should be striped.

Exhibit 1-(b) compares the MOEs produced by the three models. All models produced similar total travel. As expected, due to congestion, INTEGRATION did have a few deferred departures at the end of the simulation period which resulted in a slightly lower VMT. The total delay estimate is very large for INTEGRATION, but its total time and average speed estimates are not greatly dissimilar from the estimates of KRONOS whose total time and average speed are 15% lower and 14% higher than INTEGRATION's, respectively. These differences are consistent with the different base speed used for the estimation of delay (50 mph in KRONOS and free-flow speed—about 60 to 65 mph—in INTEGRATION and KWaves98).

KWaves98 predicted congestion relief much earlier than the other two models, as seen in Exhibit 1-(c). KRONOS and KWaves98 produced similar speed profiles over time for point A (on-ramp merge). KRONOS and INTEGRATION produce similar speed profiles over time for point B (off-ramp diverge). KWaves98 predicted that the on-ramp is the sole bottleneck and produced free flow speeds throughout the simulation period for point B.

INTEGRATION produced the longest queue of 2.61 miles; it started at about 35 minutes and did not dissipate until the end of the simulation. KRONOS produced a queue of 1.11 miles; queuing started at 40 minutes and dissipated at 95 minutes. KWaves98 produced a queue of 0.06 miles prior to link 4; queuing started at 60 minutes and dissipated at 75 minutes.

3.2.   Model Sensitivity

Basic explorations on the effects of controlled changes of critical inputs on MOEs were done. Specifically, the degree to which model outputs are affected by the freeway cross section, capacity and jam density was assessed. The results are summarized in Table 2. Once the mainline was increased from 3 to 4 lanes, there were no deferred departures for INTEGRATION and its total VMT increased by 7%. As expected, VMT did not change for KWaves98 and KRONOS. Consistent with expectations, all models produced lower delay and higher average speeds. KRONOS and KWaves98 predicted that the addition of one mainline lane would resolve the merging and diverging weaving in section A-B.

The increase in capacity (Q_{max}) by 10% also led to intuitive results from all three models. This change affected INTEGRATION the most; it produced a much lower delay and an average speed equal to that estimated by KRONOS. The 10% increase in jam density had no effect on KWaves98, a slight effect on KRONOS and a modest effect on INTEGRATION. The effect on KRONOS is intuitive: The 10% increase in k_j produced a minute increase in average speed (not shown due to rounding) which is reflected by a 1% reduction in delay. The increase in delay and decrease in speed observed in INTEGRATION's output shows that it is sensitive to k_j particularly in merging sections. The final product of increased delay may seem counterintuitive at first. However, it is the outcome of improved merging at the two on-ramps [see Exhibit 1-(a)] which resulted in a greater volume being released downstream. These heavier and earlier arrivals worsen the queuing at the divergence segment which INTEGRATION models as the worst bottleneck. This, in turn, caused a net increase in delay.

Overall, the three software showed sensitivity to important factors, particularly to capacity expressed by the number of lanes or the Q_{max} per lane. Macroscopic software such as KRONOS and KWaves98 may overestimate the benefit of adding a lane to the freeway mainline. On the other hand, KRONOS and KWaves98 are less sensitive to jam density which is welcome from a practical stand point given the difficulty and uncertainty in estimating k_j with field data.

3.3.   Simple Freeway Network with Moderate-to-Heavy Traffic and Incident

This case study utilized the same network and volumes, and investigated an incident at point B. The incident was defined as follows: 15 minutes into the simulation capacity dropped from 3 lanes to 1 lane; 10 minutes later capacity partially recovered to 2 lanes; and, 10 minutes later capacity recovered fully.

The three models produced comparable total travel and similar trends in average speed and spot speed at point A. KRONOS and INTEGRATION produced identical average speeds. KRONOS and INTEGRATION also produced similar profiles for speed at points A and B as well as for average speed. KWaves98 basically predicted relief much earlier than the other two models and, as a result, its speed and delay differ markedly from the other two models.

INTEGRATION produced the longest queue of 5.22 miles; it started at about 15 minutes and dissipated at 115 minutes. KRONOS produced a queue of 3.81 miles; it started at 15 minutes and dissipated at 70 minutes. KWaves98 produced a queue of 4.89 miles which started at 15 minutes and dissipated at 70 minutes.

3.4.   Real Case with Heavy Traffic

This section presents simulation of the east bound H-1 freeway in Honolulu. The simulated length begins with the 3-lane SR-78 (Moanalua Freeway, an interstate-class facility) which merges with the 2-lane H-1 freeway as shown in Exhibit 2-(a). The facility continues as EB H-1 freeway, heading into central Honolulu. The simulation was done with data from 6:00 A.M. to 8:00 A.M. collected on September 15, 1998. Given the early start of the business day in Honolulu (around 7:30 A.M.), heavy congestion is observed shortly after 6:00 A.M.

SR-78, H-1, Likelike on-ramp and the Liliha on-ramp have average demands of 1,546, 1,370, 955 and 667 veh/hr/ln, respectively. O-D matrices for use with INTEGRATION and KWaves98 were estimated from on- and off-ramp volumes which were counted from videotapes using the AUTOSCOPE and by manual checks of selected ramps and mainline segments. Actual speeds were obtained with AUTOSCOPE analysis of tapes recorded on September 15, 1998, from two locations. The first location was on the right lane of SR-78 prior to merging with the H-1 freeway (6:45 to 8:00 A.M.); this location is close to point 1 in Exhibit 2-(a). The second location was on the right lane of the H-1 freeway prior to merging with the Liliha on-ramp (6:30 to 8:00 A.M.); this location is close to point 5 in Exhibit 2-(a). Additional specifications for the simulations which produced the results shown in Exhibit 2 are given below:

1. Due to the need to replicate the very heavy congestion observed on this section of freeway, an extraodrinarily high jam density of 300 veh/mi/ln was used with

INTEGRATION and KWaves98. A reasonable $k_j = 150$ veh/mi/ln was used with KRONOS. When the default KRONOS $k_j = 186$ veh/mi/ln was used in INTEGRATION, more than 10% of observed traffic did not occur (deferred departures). KWaves98 would produce a "fatal error" and cease processing.

2. INTEGRATION also required extraordinarily high capacity to avoid a large number of deferred departures on two on ramps. The capacity of links from the Likelike on-ramp link to the Vineyard off-ramp was set to 3,000 veh/hr/ln and all others were set to 2,700 veh/hr/ln. Similarly, capacities of 3,000 veh/hr/ln were used with Kwaves98 in order to replicate observed traffic. For KRONOS, the capacity on all links was set to 2,000 veh/hr/ln.

3. INTEGRATION did not model well the section of an on-ramp which is connected to an off-ramp with an auxiliary lane. Striping was attempted in this section (section from point 1 to point 2 in Exhibit 2) but it produced the same speed in all time intervals for all 5 points, thus, striping was not adopted.

Exhibit 2-(b) compares the MOEs produced by the three models. They produced nearly identical total travel. The onset of congestion [observe the actual data represented by the thicker line in part (c)] is captured best by KRONOS. KRONOS speed estimates are lower by about 10 mph at point 5 [graph (d)], but it has the best overall agreement with the instrumented vehicle statistics in graph (e). INTEGRATION does well at point 1 and better than KRONOS in point 5. However, its speed estimates at points 3, 4, and 5 differ by more than 15 mph from the instrumented vehicle averages. KWaves98 speed estimates present notably large lags from actual speed estimates. However, during the very congested period between 7:00 and 8:00 A.M., most of its speed estimates at points 1 and 5 are close to those observed in the field.

The three models predicted different maximum queue lengths with errors ranging between −65% and +30% based on local experience of queue formation measuring about 5 miles. INTEGRATION produced a queue of 3.4 miles, which is rather short (~−30%). KRONOS' max queue reached 6.4 miles (~+30%). KWaves98 produced a small queue of only 1.7 miles (~−65%). Notably, queue build-up in INTEGRATION and KWaves98 was affected by the large capacities used to obtain observed volume levels.

4.   CONCLUSIONS AND DISCUSSION

Three inexpensive software packages capable of simulating freeway traffic operations were tested. Traffic analysts should find all three software to be intuitive and straight forward in their application. Two of them, KRONOS and INTEGRATION produced reasonable results under most circumstances. Density output from these models can be used for assessing LOS based on the HCM. This task would be easier with INTEGRATION which allows for the collection of speed, volume and density data at any location with virtual detectors. All models also had flaws, which are summarized below.

INTEGRATION produced acceptable results for all cases examined, however, on segments which include an on- and an off-ramp connected with an auxiliary lane, it did not simulate well the lane-changing of merging vehicles (most accumulated at the neighborhood of the off-ramp). Under heavy traffic conditions, these vehicles often make a complete stop prior to accepting a gap on the mainline, which is unrealistic and results in

excessive congestion on those links. Lane-striping could not correct this problem for the congested conditions modeled in the case studies. Lane striping is more effective on regular off-ramps which have their own deceleration length.

KRONOS required the fewest modifications to default parameters to achieve good results. The proper adjustment of capacity of freeway links with acceleration and deceleration lanes is necessary for simulating merging accurately. Disadvantages include unforgiving user-input overrides and the tendency to overestimate the benefit of freeway lane addition, particularly for cases where the bottleneck is mostly attributable to heavy weaving among neighboring on- and off-ramps.

KWaves98 applies only to freeway operations with heavy traffic and it has a marginal performance. KWaves98's triangular modeling of the speed-flow relationship causes it to under-estimate the formation of congestion (late onset of congestion) and over-estimate the dissipation of congestion (early relief).

All three models yielded comparable results for incident simulation. The three software showed sensitivity to important factors, such as the number of lanes and lane capacity. KRONOS and KWaves98 are less sensitive to jam density which is desirable given the difficulty and uncertainty in estimating k_j with field data.

INTEGRATION and KRONOS can produce acceptable results, based on the cases examined. They have the benefit of several years of development and refinement. They need additional improvements such as those mentioned above. Updated versions of both are being developed. KWaves98 is an early prototype that has not had the benefit of testing and refinement over time, thus, its use outside research may be unwise.

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TABLE 1   Comparison of Attributes of the Tested Freeway Simulation Software

	INTEGRATION 2	KRONOS 8	KWaves98
Input	**B a s i c**	**B a s i c**	**B a s i c**
	Simulation duration	Simulation duration	Simulation duration
	Output time interval	Output time interval	
	Time step =1/10 second, fixed	Time step = 1 second, fixed	Time step = user-adjustable
	Geometry: node coordinates, link connections and number of lanes for each link	Geometry: sequential addition of pipeline, lane change and ramp segments	Geometry: nodes, link connections and number of lanes for each link
	Capacity in veh/hr/ln	Capacity in veh/hr/ln	Capacity in veh/hr/ln
	Q-U function: free flow speed, speed at capacity, jam density	Q-K function: jam density, critical density, maximum flow, ka ($u=u_f$ for k< ka)	Q-K function: Free flow speed, jam density
		Minimum delay speed (delay is measured for $u<u_{min}$)	
	Traffic composition: up to 5 vehicle types (see below)	Traffic composition: models 3 types of vehicles	
	O-D demand with uniform or random departure headways	Demand for initial segment and all on-and off-ramps	O-D demand
	O p t i o n a l	**O p t i o n a l**	**O p t i o n a l**
	Detectors	Initialization demand	Backward wave speed
	Incident: location, duration of capacity event, effect of lanes	Incident: location, duration and affected distance	Incident: location and duration of capacity event
	Ramp meters	Mainline downstream demand	
	Lane striping	Mainline congestion information	
	High occup. vehicles (defined as a veh. type)	Fuel consumption and pollution level	
	ITS and routing provisions (defined with veh. types)	Capacity limits or congestion on ramps	
Output	Statistics of total travel, total time and average speed by link and by time interval	Statistics of total travel, total time, total delay and average speed by segment and interval; also cumulative	Total travel, total time, total delay and average speed for links and entire freeway
	Time-variant speed, flow at detectors	2-dimensional and 3-dimensional flow, density, speed contours versus time and distance	2-dimensional and 3-dimensional flow, density, speed contours versus time and distance
	Microscopic animation while simulation executes; ability to pan, zoom and focus on network details	Macroscopic flow emulation: density-based colored-coded scan of modeled freeway for each time interval	Cumulative flow curve for each segment
	Simulation Run Error file	Representation of freeway geometry	Q-U-K diagrams
	Aggregate fuel consumption and pollution estimates	Fuel consumption and pollution estimates	

TABLE 2 Sensitivity Test Results Using the Case in Exhibit 1 as Base, (a) Change Mainline from 3 to 4 Lanes, (b) Increase Q_{max} by 10%, (c) Increase k_j by 10%

		Measures of Effectiveness			
		Total travel (veh-mi)	Total time (veh-hr)	Total delay (veh-hr)	Average Speed (mph)
(a)	INTEGRATION 2.0	93701	1894	368	49
	Diff. from base	*7%*	*-15%*	*-54%*	*25%*
	KRONOS 8.0	87489	1487	0	59
	Diff. from base	*-1%*	*-22%*	*-100%*	*27%*
	KWaves 98	89655	1379	0	65
	Diff. from base	*0%*	*-7%*	*-100%*	*8%*
(b)	INTEGRATION 2.0	93538	1775	253	53
	Diff. from base	*7%*	*-20%*	*-68%*	*35%*
	KRONOS 8.0	87438	1646	26	53
	Diff. from base	*-1%*	*-14%*	*-87%*	*15%*
	KWaves 98	89655	1378	0	65
	Diff. from base	*0%*	*-7%*	*-100%*	*8%*
(c)	INTEGRATION 2.0	90651	2370	895	38
	Diff. from base	*4%*	*7%*	*12%*	*-3%*
	KRONOS 8.0	88314	1906	200	46
	Diff. from base	*0%*	*0%*	*-1%*	*0%*
	KWaves 98	89655	1488	109	60
	Diff. from base	*0%*	*0%*	*0%*	*0%*

(a)

(b)

	MOE	Total travel (veh-mi)	Total time (veh-hr)	Total delay (veh-hr)	Average Speed (mph)
1	INTEGRATION 2.0	87312	2221	800	39
2	KRONOS 8.0	88163	1906	203	46
3	Kwaves 98	89655	1488	109	60

(c)

(d)

(e)
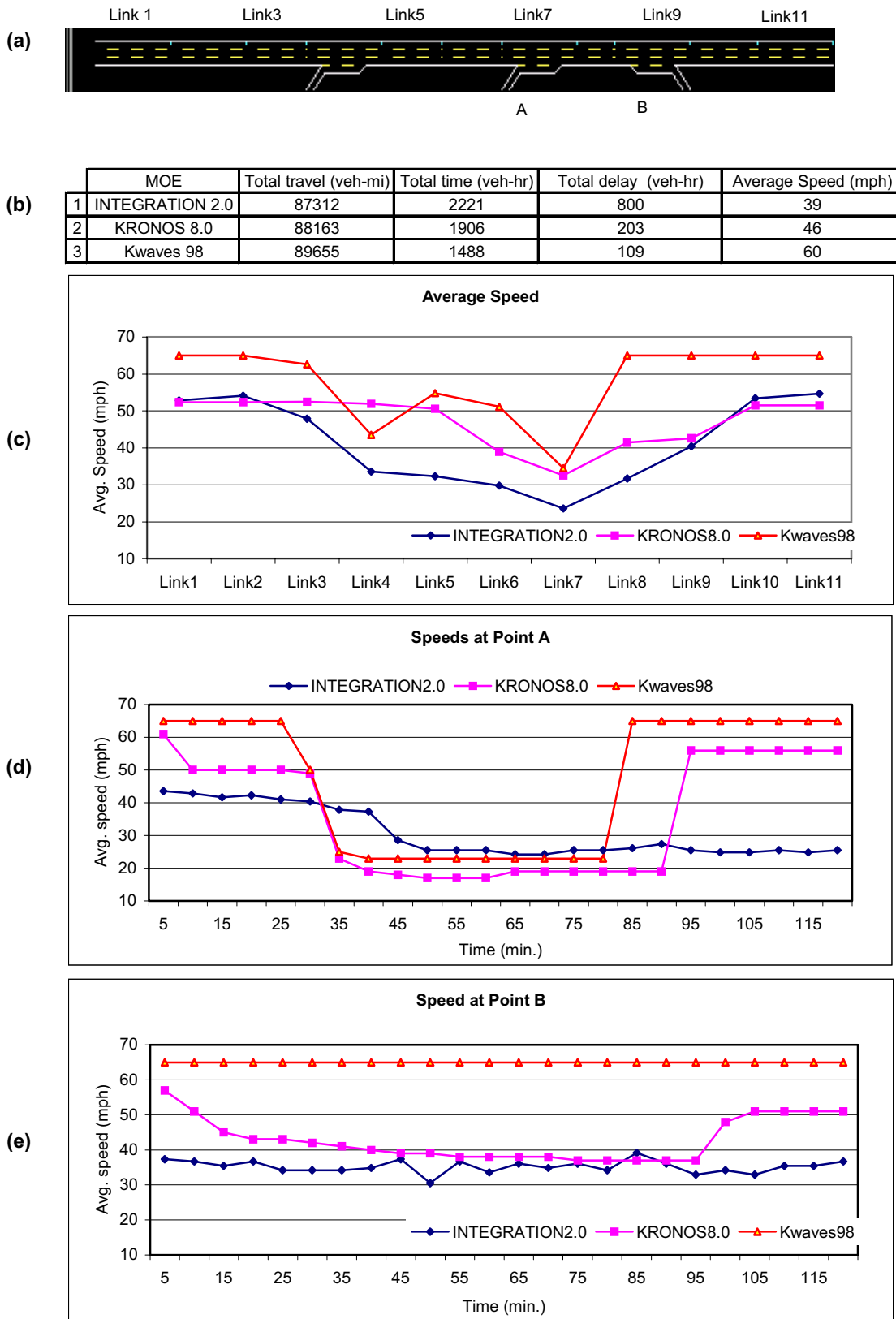
EXHIBIT 1   Freeway alignment and results for a simple network with moderate-to-heavy traffic.

(a)

SR-78	EB H1-on	Likelike-off	Likelike-on	Vineyard-off	Liliha-on
Link2	Link4	Link6	Link8	Link10	Link12

1   2   3   4   5

(b)

	MOE	Total travel (veh-mi)	Total time (veh-hr)	Total delay (veh-hr)	Average Speed (mph)
1	INTEGRATION 2.0	77346	2167	893	36
2	KRONOS 8.0	77516	2846	1347	27
3	Kwaves 98	77470	1939	747	40

(c)

Speed at Point 1

- INTEGRATION2.0
- KRONOS8.0
- Kwaves98
- Actual (AUTOSCOPE)

Speed (mph) / Time

(d)

Speed at Point 5

- INTEGRATION2.0
- KRONOS8.0
- Kwaves98
- Actual (AUTOSCOPE)

Speed (mph) / Time

(e)

Average Speed (6:30-8:00 A.M.) at Points 1…5

- Actual (Instrumented vehicle)
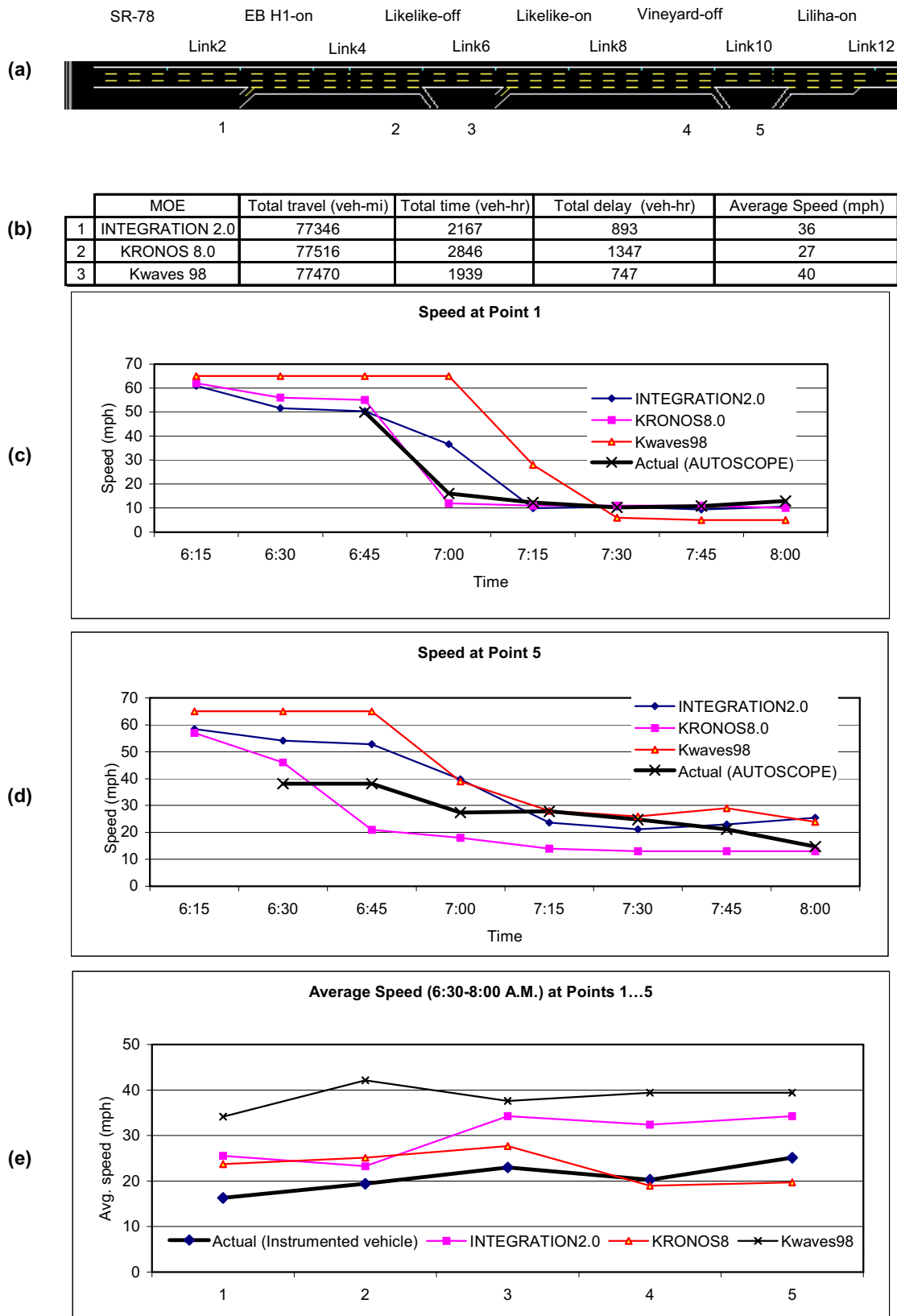- INTEGRATION2.0
- KRONOS8
- Kwaves98

Avg. speed (mph)

EXHIBIT 2   Eastbound H-1 Freeway alignment and results for real case with heavy traffic.